

Temperature and field dependence of Dynamics in the Electron-Glass

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Abstract

We describe several experimental methods to quantify dynamics in electron glasses and illustrate their use in the glassy phase of crystalline indium-oxide films. These methods are applied to study the dependence of dynamics on temperature and on non-ohmic electric fields at liquid helium temperatures. It is shown that over a certain range of temperature the dynamics becomes slower with temperature or upon increasing an applied non-ohmic field, a behavior suggestive of a quantum-glass. It is demonstrated that non-ohmic fields produce qualitatively similar results as raising the system temperature. Quantitatively however, their effect may differ markedly. The experimental advantages of using fields to mimic higher temperature are pointed out and illustrated.

PACS numbers: 72.80.Ny 73.61.Jc

I. INTRODUCTION

Glasses are characterized by a slow approach to equilibrium, a process often described as a journey through a phase space composed of many local energy-minima that are separated by barriers [1]. The motion through this phase space is hindered by these barriers; the system is trapped for relatively long time in one of the local minima before it manages to cross a barrier and move to another metastable state. At finite temperatures, crossing a barrier is usually assumed to be controlled by thermal activation. Alternatively, the barriers may be crossed by quantum mechanical tunneling, and this will become the dominant mechanism at sufficiently low temperatures. It should be possible to tell the quantum-mechanical regime from the thermally activated regime by the dependence of the glassy dynamics on temperature T . Dynamics in the classical glass speeds up as the temperature increases, and this feature has been studied extensively in many systems. The case in the quantum scenario is less clear. It is commonly believed that, as long as the barrier does not change, tunneling is temperature independent. However, in a dissipative environment, which seems a relevant consideration for the situation at hand [2], tunneling rate γ may depend on temperature; γ may increase or decrease with T depending on the interplay between the barrier parameters, the coupling of the tunneling object to the environment, and the temperature range [3].

In this paper we describe several methods to probe the dynamics in electron glasses. These are used to study the dynamics in the glassy phase of indium-oxide films as function of temperature, non-ohmic electric field F , and disorder. A previous work, based on the aging behavior, showed that the dynamics in this system does not slow down as T is lowered [4]. The more sensitive methods used here demonstrate that over some range of temperatures and sample parameters, the dynamics may actually *slow down* with temperature. Similar result is observed when instead of increasing the sample temperature the excess energy of the electrons is increased by applying non-ohmic electric fields. It is demonstrated that increasing the field affects various quantities in the

same direction as raising the temperature although quantitatively their effect may be quite different. The experimental advantages of using non-ohmic fields to mimic higher temperatures conditions are utilized to illustrate some unique features of the electron glass.

II. EXPERIMENTAL

A. Sample preparation and measurement techniques

Several batches of In_2O_{3-x} samples were used in this study. All were thin films of crystalline indium-oxide (30-50Å thick, with lateral dimensions of $\simeq 1 \times 1$ mm). These were e-gun evaporated on 110μm cover glass. The sheet resistance R_{\square} of the samples was limited to the range 1MΩ-2GΩ at $T = 4.11K$. This range includes samples with large enough disorder to exhibit significant glassy effects, and small enough sheet resistances to allow reasonably high frequencies for the ac conductance measurements (to facilitate a reasonable temporal resolution). Gold film was evaporated on the backside of the glass substrate and served as a gate electrode (configuring the sample as a field-effect device). Conductivity of the samples was measured using a two terminal ac technique employing a 1211-ITHACO current preamplifier and a PAR-124A lock-in amplifier. The measurements as function of non-ohmic fields were performed with the samples immersed in liquid helium at $T = 4.11K$ held by a 100 liters storage-dewar. Measurements as function of temperatures were made in a 3He refrigerator with the samples in vacuum attached to a copper stage along with a Ge-thermometer. For these measurements, the ac voltage bias was small enough to ensure ohmic conditions. Temperature was controlled with Oxford Instruments ITC503 employing a RuO thermometer. Fuller details of sample preparation, characterization, and measurements techniques are given elsewhere [5].

B. Procedures for measuring dynamics

The main goal of this work was to characterize the dynamics in the electron glass and its dependence on external parameters in particular the effect of temperature, and electric fields. The natural (history free) relaxation law of the electron glass is logarithmic, a behavior that may extend over more than 5 decades in time [6]. Following e.g., a quench-cooling from high temperature to $\approx 4K$, the sample conductance relaxes slowly, and depends on time as $G(0) - a \log(t)$ (where $G(0)$ is the conductance at $T = 4K$ immediately after the cool-down). Having no characteristic time scale, such a relaxation law does not allow for a unique definition of a relaxation time τ . It is possible however to give an empirical scheme that yields a measure of dynamics. In the following we describe three such methods.

1. The two-dip-experiment

The first example is the two-dip-experiment [5], which involves the following procedure. First, the sample is allowed to equilibrate at the measuring temperature with a voltage V_g^o held at the gate. Then, a $G(V_g)$ trace is taken by sweeping V_g across a voltage range straddling V_g^o . The resulting $G(V_g)$ exhibits a minimum centered at V_g^o which reflects an inherent feature of a hopping system - its equilibrium conductance is at a local minimum [7]. At the end of this sweep, a new gate voltage, V_g^n , is applied and maintained at the gate between subsequent V_g sweeps that are taken consecutively at latter times (measured from the moment V_g^n was first applied). Each such sweep reveals two minima; One at V_g^o which fades away with time, and the other at V_g^n whose magnitude increases with time. The two-dip-experiment then amounts to studying the dynamics of the "forming" of a cusp at a newly imposed V_g^n and the "healing" of an 'old' cusp at V_g^o . A characteristic-time τ is defined as the time at which the amplitude of the cusp at V_g^n just equals the amplitude of the cusp at V_g^o . This procedure is experimentally well-defined, and it is fairly independent of the particular relaxation law. The two-dip-experiment has been used before to study the dependence of the dynamics on carrier concentration, and on magnetic field [7].

2. The double-conductance-excitation method

The main method we use in this work to quantify dynamics is a variation on the two-dip-experiment. The procedure is illustrated in figure 1. Starting with the sample with a voltage V_g^o held at the gate, and equilibrated under the fixed external conditions (temperature T , or electric field F), one monitors the conductance as function of time $G(t)$ to obtain a baseline conductance.

FIG. 1: Typical run of the double-conductance-excitation protocol. The dependence of the conductance G on time is plotted as squares and the gate voltage as dashed line. The sample has $R_{\square} = 22.5M\Omega$ is 30\AA thick and $1\times 1\text{mm}$ lateral dimensions, and measured under $F = 30V/cm$. A constant waiting time $t_w = 3\text{min}$ has been used for all experiments in this work. The bath temperature is $T = 4.11K$.

Then, the gate voltage is switched to V_g^n and is maintained there for a certain "waiting-time" t_w . Finally, the gate voltage is switched back to V_g^o , and $G(t)$ is measured for an additional period of time. Here we are interested in the ratio $\delta g(0)/\delta g(t_w)$ which is a measure of relaxation time defined for a fixed t_w . Actually, this procedure is just the gate-protocol for aging described elsewhere [4]. The difference is that in the aging protocol one varies t_w under fixed external conditions (i.e., T or F) whereas here t_w is fixed and we vary T (or F). A constant value $t_w = 180\text{sec}$ was used for all the experiments reported here.

To see why $\delta g(0)/\delta g(t_w)$ is related to dynamics note that $\delta g(t_w)$ is a measure of how far the sample G has drifted in phase-space during t_w towards its equilibrium state (set by V_g^n and the external conditions). If, for example, a full equilibrium is reached during t_w , $\delta g(t_w)$ will obviously equal $\delta g(0)$. If, on the other hand, relaxation is infinitely slow, $\delta g(t_w)$ will be zero. The initial conductance jump $\delta g(0)$ is a proper normalization; when the external conditions are changed, the degree of sample excitation (when V_g^n is switched to V_g^o or *vice versa*) will in general change too, and it will be reflected in $\delta g(0)$. Likewise, the value of δg_{eq} (c.f., figure 1) should be measured for each run because its value usually depends on the external conditions. The origin of δg_{eq} is the equilibrium field effect, namely, the change of the equilibrium conductance when V_g^n is switched to V_g^o (which in turn is due to the energy dependence of the *thermodynamic* density of states). This physical quantity is reflected in an anti-symmetric contribution to the field effect as illustrated in figure 2 for samples with different degrees of

III. RESULTS AND DISCUSSION

4. Temperature dependence of the dynamics

FIG. 2: The normalized field effect at $T = 4.11K$ for some of the samples used in this work. Note that the relative amplitude of the anomalous cusp increases with disorder, and is essentially zero for the sample with $R_{\square} = 0.55M\Omega$. The dashed lines reflect the slopes of the equilibrium field effect. These slopes obviously depend on disorder, as well as on temperature and electric field (c.f., figures 4 and 5 respectively).

disorder. The values of $\delta g(0)$ and $\delta g(t_w)$ are extracted from the $G(t)$ data as in figure 1 as follows. First, the times t_1 and t_2 where V_g^n reached its final value, and V_g^o is reinstated respectively are noted. These are used as the origin ($t = 0$) for the two relaxations of $G(t)$; the first after the V_g^o to V_g^n switch, the second after the switch back. Each such $G(t)$ start out as $G(t_0) - a_{1,2} \log(t/t_0)$ (the first, being history-free, persists as a log throughout t_w , the second is logarithmic only for $t \ll t_w$). The respective values of $G(t_0)$ are found by extrapolation (t_0 is the resolution time of the measurement, typically $t_0 = 1$ sec.), and are used to calculate $\delta g(0)$ and $\delta g(t_w)$ by subtracting the appropriate baseline. This method should be easier to implement in systems such as granular Al where the anti-symmetric part of $G(V_g)$ is negligible relative to the anomalous cusp in $G(V_g)$ [8] and thus there is no need for the additional measurement of δg_{eq} .

3. A single-conductance-excitation

A quick way to assess dynamics is based on monitoring the relaxation of the excess conductance created, say, by a V_g switch. Then the resulting data $G(t_0) - a \log(t/t_0)$ is normalized by $\delta G(t_0)$ and the prefactor $a/\delta G(t_0)$ is used as a measure of the dynamics. This normalization is not as reliable as the one used in the previous method because it does not preclude the possibility that the excitation itself may depend on the external conditions (namely, non-linear effects). Note also that unless δg_{eq} is negligible it has to be measured separately and be used in the analysis. This method will be used here only as a further illustration of the central finding of our study.

Measurements of glassy features as function of temperature are more complex and demanding than it may be at first realized. This is mainly due to the exponential temperature dependence of the conductance of electron glasses. Note that a pre-requisite for observing non-ergodic effects in these systems is that the sample is in the strongly localized regime. In two dimensions, that means that R_{\square} is larger than the quantum resistance $h/e^2 \approx 25k\Omega$. In fact, we observe glassy behavior only in samples with $R_{\square} \geq 200k\Omega$, (see, for example, figure 2 and figure 4). Such samples naturally exhibit exponential G versus T . This exponential sensitivity of $G(T)$ mandates a tight control over the bath temperature since the glassy part of G is of the order of only few percents. For the sample used here it was necessary to establish a $\pm 1mK$ temperature stabilization at each instance of the studied range.

Another problem that makes these measurements a time consuming endeavour is an inherent memory effect; Changing T leaves the system with memory of the previous conditions, and a long equilibration period is required before a measurement at the new T may commence [9]. This effect will be discussed and illustrated later (figure 11).

Once the bath temperature has stabilized on the target T , a record of $G(t)$ was initiated to detect any drift that still exists due to the glassy relaxation. The latter could be distinguished from the drift/fluctuation of the bath temperature by the reading of a calibrated Ge-thermometer attached to the sample holder. The measurements that are the basis for the results in figure 3 included, at each temperature, a double-conductance-excitation procedure as well as a $G(V_g)$ scan such as that shown in figure 4 from which the respective value of δg_{eq} was obtained. The $G(t)$ data of the conductance-excitation protocol was corrected for the spurious temperature fluctuations by the respective trace of the Ge-thermometer. Finally, the values of $\delta g(0)$ and $\delta g(t_w)$ were calculated as described above using the temperature-corrected $G(t)$ in conjunction with δg_{eq} from the data in figure 4.

The results of the more elaborate two-dip-experiment performed at two temperatures in the studied range are also shown in figure 3 for comparison. Both methods yield the same result; the dynamics in this particular range of disorder and temperature becomes somewhat *slower* with T . The dependence on temperature is rather weak; for a factor of 3 in the range of T , the average conductance changes by a factor of 25 while the characteristic relaxation time τ changes by only 30%. This slowing down of the dynamics with temperature is consistent with a tunneling in a dissipative environment scenario [3]. We were not yet able to extend these measurements to higher temperatures. In addition to the technical difficul-

FIG. 3: The dependence of the dynamics parameter $\delta g(0)/\delta g(t_w)$ on temperature. This is based on the double-conductance-excitation using a constant $t_w = 3$ min (squares) and τ based on the two-dip-experiment (circles). Data are for a 50\AA thick and $1\times 1\text{mm}$ lateral dimensions sample with $R_{\square} = 212k\Omega$ at $T = 4.11K$.

FIG. 4: The normalized field effect at different temperatures for the same sample as in figure 3. Note the dependence of the asymmetric component of the field-effect on temperature as well as the fast diminishment of the anomalous cusp amplitude with T .

ties noted above, the glassy effects on which the methods is based die out exponentially with temperature. This can be clearly seen in the way the anomalous cusp is diminished with T (figure 4). It should be noted that there is no a-priori reason that the observed trend in $\tau(T)$ will change sign before the glassy effects become immeasurably small. The transition to a glassy phase in the electron glass is a quantum phase transition [10], and for a two-dimensional system there may be no ‘glass temperature’ except at $T = 0$. Observation of glassy effects at a finite T would still be possible as long as $k_B T \ll E_C$ (where E_C is the relevant interaction energy) in the same

FIG. 5: The normalized field effect measured at different values of the electric field for the sample in figure 1. The dashed lines represent the slopes of the equilibrium field effect. These are used to estimate the relevant δg_{eq} (see text).

vein that insulating features are observable in Anderson insulators at finite T while, strictly speaking, the metal-insulator transition occurs at $T = 0$.

5. Dependence on non-ohmic field

Studying the dynamics as function of F entails several advantages that make the process easier than the respective study as function of T : Switching from one value of F to another is fast and accurate, the signal/noise naturally improves with F (as long as F is much smaller than a critical value see: [11]), and working with a massive ^4He Dewar as the base temperature makes it feasible to perform long runs without thermally-cycling a given sample. In the experiments detailed below, the equilibration times used prior to running a double-conductance-excitation protocol was typically several hours. It is important to realize though that even such an extended period of equilibration does not guarantee that the measurement is performed at equilibrium. In fact, relaxation from an excited state in these systems were observed to persist for at least several days [6]. As it is impractical to wait that long at each field (or temperature), one has to acknowledge the possibility that the results may deviate from their true value. We did however test the sensitivity of our procedure to variation in the equilibration time and found that, within the experimental error, waiting more than 4 hours had a negligible effect on the outcome.

The same protocol was used here as in that leading to figure 3 above. For each sample, and at each value of F , a $G(V_g)$ scan was taken to get the value of δg_{eq} . An example is shown in figure 5 for one of the samples.

Figure 6 shows the dependence of the dynamics on F for a $\text{In}_2\text{O}_{3-x}$ sample at three different states of disorder characterized by the sheet resistance at $T = 4.11K$. These were produced from a single batch of indium-oxide

FIG. 6: The dependence of the dynamics parameter $\delta g(0)/\delta g(t_w)$ on electric field for three samples with different disorder (upper graph). Lower graph shows the dependence of the conductance of these samples on field. The bath temperature is $T = 4.11K$. Dashed lines are guide for the eye.

by UV-treatment as described elsewhere [12]. Also shown (lower graph) is the dependence of the conductance of these samples on the field. Two observations can be made from the figure; first, for a given field, $\delta g(0)/\delta g(t_w)$ increases with disorder, which is consistent with a previous study based on the two-dip-experiment [7] (note that a larger $\delta g(0)/\delta g(t_w)$ means slower relaxation). Secondly, $\delta g(0)/\delta g(t_w)$ increases with F , and there is an obvious correlation between this dependence and the deviation from ohm's law of the respective sample (lower graph). In particular, in the small field limit the results for both $G(F)$ and $\delta g(0)/\delta g(t_w)$ tend to become independent of F as one expects for the linear response regime.

The increase of $\delta g(0)/\delta g(t_w)$ with F seems to mimic the slowing-down with T trend noted in figure 3 above. It is therefore tempting to cast the results of the upper graph in figure 6 as function of some effective temperature T^* . One way to do that is by combining the $G(F)$ data with the conductance versus temperature $G(T)$ of these samples exhibited in figure 7. In essence, this procedure is tantamount to using the average conductance as a thermometer. Reservations with this 'effective temperature' approach will be mentioned later. The results of this procedure are given in figure 8, which for all three samples show a similar behavior of the dynamics as that exhibited in figure 3 as function of temperature.

FIG. 7: The dependence of the (ohmic) conductance G on temperatures for the samples in figure 6. These data were taken by raising the probe above the liquid helium bath, then slowly lowering it back while monitoring G and the temperature by the reading of the Ge thermometer attached to the sample stage.

FIG. 8: The dependence of the dynamics parameter $\delta g(0)/\delta g(t_w)$ on effective temperature T^* using the data of figure 6 and figure 7 (see text for details).

The observation of a slower dynamics at higher temperatures is not a universal feature of the electron glass. This dependence has been seen so far only in crystalline indium-oxide films and over a limited range of temperatures. In a preliminary study [13] employing 50Å thick In_2O_{3-x} films doped with 3.4% Au and compared their dynamics versus F with that of undoped In_2O_{3-x} that otherwise had similar characteristics. Two pairs of samples (Au doped and undoped) were studied so far with $R_{\square} \approx 1.5M\Omega$ and $\approx 30M\Omega$ and the following results were obtained: The undoped samples consistently showed virtually the same F dependence as in figure 6. By contrast,

over the same range of fields ($10^{-1} - 10^2 V/cm$), the two Au-doped samples exhibited much weaker F - dependent dynamics, in fact, within the experimental error, the dynamics was independent of F . A possibly relevant difference between the two types of materials appears to be a wider anomalous cusp which suggests a higher density of carriers in the Au-doped samples [14]. It would be interesting to see if using a material with still higher carrier concentration will result in the opposite trend of dynamics versus T . This may be attained for example with amorphous indium-oxide films that can be prepared with a much wider range of carrier concentration than can be achieved by doping In_2O_{3-x} [14].

For the time being we shall focus on the dynamics of the crystalline samples that exhibit dynamics slowdown with either T or F . This unusual dependence is interesting enough to justify further efforts to establish its existence even for just its uniqueness; we are not aware of any other glass that exhibits this kind of behavior. Moreover, it would seem that such a dependence might be reconciled with quantum relaxation making the electron glass a prime candidate for such studies.

In the following we describe two experiments demonstrating qualitatively that the dynamics of a crystalline In_2O_{3-x} slows down upon an increase in the non-ohmic F . In the first experiment, we used the single-conductance-excitation method, and generated normalized relaxation curves measured under different non-ohmic fields. These are plotted in figure 9 along with the resistance versus field characteristics of this sample. The slowing down of the dynamics is clearly reflected in the logarithmic slopes of the relaxation curves becoming smaller as F increases. (Note however that the values of δg_{eq} were not excluded from the data in this case, and therefore the effect is somewhat smaller than that reflected in the figure).

The second experiment, utilizing the same sample, is the analog of the temperature excursion protocol (referred to sometimes as ‘rejuvenation’ in the dielectric-glass and spin-glass communities [15]). In the experiment, shown in figure 10, the sample is initially relaxing from an excited state (produced by a quench-cool or gate switch), and its conductance versus time is recorded for $t_1 \approx 100$ sec while under a relatively high F_1 . Then, F_1 is suddenly switched to a near-ohmic field F_2 , and $G(t)$ (naturally now lower than when under F_1) is measured for $t_2 \approx 1300$ sec before F_1 is re-instated, and the relaxation of G is extended for $t_3 \approx 27,000$ sec. Note that the $G(t)$ during t_3 is a natural extension of the purely logarithmic relaxation of the t_1 period, which is the natural relaxation law of the electron glass [5, 6]. However, to get the $G(t)$ in these two regions to match as well as in the figure, the time axis of the t_3 region was *right-shifted* by ≈ 400 sec. This is precisely the opposite direction that is necessary to match the respective relaxations in the ‘classical’ glasses where the dynamics slows down upon cooling [15]. Note also that the logarithmic slope of the relaxation during t_2 is consistent with a *faster* dynamics

FIG. 9: Results of a single-conductance-excitation protocol at various electric fields. Sample is 52\AA thick, with $1.1 \times 1\text{mm}$ lateral dimensions and has $R_{\square} = 52.5 M\Omega$ at $T = 4.11 K$ (in the limit of small field). Note that the logarithmic slopes get progressively smaller when F gets further into the non-ohmic regime (This can be seen in the lower graph that depicts the resistance versus F of this sample).

at the lower ‘effective T ’.

6. Is a non-ohmic field equivalent to a higher ‘effective’ temperature?

As explained above, using high fields has some technical advantages over raising the temperature. The question however is to what degree the effects produced by a large F are the same as those produced by raising T . In general, the state of the system under large F would be different than that achieved by a higher T . This is true in the diffusive regime [16], in the hopping regime, and whether or not the system is glassy. One may be assured that ‘heating’ and ‘non-equilibrium’ are indistinguishable only if the relevant distribution functions assume their *equilibrium* form and with the *same* temperature. In terms of measured quantities however, the difference between heating and a high-field situation may be small when the various scattering lengths (for momentum, and energy relaxations) are much smaller than the sample dimensions. The samples used here (typically, $1 \times 1\text{mm}$) are much larger than the largest scale in the

FIG. 10: The conductance versus time during a field-cycling protocol as an analog of a ‘rejuvenation’ experiment (see text). The same sample as in figure 9.

problem (which is the percolation radius that at the lowest T used here is of order 10^3\AA , the hopping length is one order of magnitude smaller). It is plausible that, under these conditions, measured quantities will be affected in the same direction by increasing either F or T , and this is the only assumption made here. We do not expect that the mapping used in arriving at T^* in figure 8 should be identical to a measurement using an equilibrium bath-temperature T that equals T^* . In fact, as the next experiment shows, warming up the sample to obtain the same G as that resulting by a non-ohmic F may lead to a *quantitatively* different effect.

Figure 11 shows the time dependence of the conductance of a sample under two different external conditions; Starting from a near-equilibrium state at $T = 4.1K$ the sample was quickly warmed up to $T = 6.2K$, which caused its (ohmic) conductance to increase by a factor of ≈ 3 . It was then kept at this T while its $G(t)$ was recorded for $\approx 1000 \text{ sec}$. Next, the sample was cooled back to $T = 4.1K$, allowed to equilibrate for 24 hours, and then it was subjected to a field F such that the conductance measured immediately after the switch to the non-ohmic field has increased to the same value ($\pm 2\%$) as the respective G immediately after the switch to $T = 6.2K$ (see figure). Then $G(t)$ was measured while holding this F at a bath $T = 4.1K$. The ensuing $G(t)$ increases with time in both cases, however the $T = 6.2K$ variant increases noticeably faster, and it may have a somewhat different functional dependence than the non-ohmic F time-trace.

The logarithmic increase of G with time under the non-ohmic field has been studied before as a manifestation of a time-dependent heat-capacity [17]. The difference between the effect of field versus that of temperature is not surprising; The field coupling to the hopping system is both inhomogeneous and anisotropic whereas temperature (via phonons) couples effectively to all regions of the sample. Aiming to set G (at a given time) at a predetermined value by raising T will generally entail quite dif-

FIG. 11: Conductance versus time after quickly raising the temperature of a sample (50\AA thick, $R_{\square} = 1.42 M\Omega$ at $T = 4.11K$ where it equilibrated for $t \geq 20$ hours) to $T = 6.2K$ (squares), and after increasing the field from its ohmic value to $F = 30V/cm$ which gave the almost the same G while keeping the sample at the liquid helium bath (circles).

ferent current-carrying network than when the same goal is accomplished by F . This difference is also relevant for the energy-balance that determines the steady-state conductance (reached for $t \geq t_{ergodic}$), which therefore will in general be different for the two routes.

The next experiment carries a double message; It is yet another illustration that F and T produce qualitatively similar effects, and it demonstrates that the concept of ‘effective temperature’ has at best a limited value for the glass state. The first half of this experiment shown in the lower graph of figure 12 is the analog of the experiment described before involving a temperature quench (see figure 10 in reference 5). Starting with the sample equilibrated for 23 hours under $V_g = 50V$ and $F_1 = 92V/cm$ a field effect scan $G(V_g)$ is taken to show the shape of the near-equilibrium anomalous cusp that characterizes these conditions. Then, F_1 is quickly reduced to $F_2 = 0.45V/cm$ and a $G(V_g)$ scan is taken consecutively at different times after the switch to F_2 . Note that the sample conductance changes in the $F_2 \rightarrow F_1$ switch by $\approx 320\%$ and this change occurs *immediately* after F_1 is set (G continues to change logarithmically after the “quench” by only $\approx 2\%$ over the next 25 hours, c.f., figure 12). By contrast, the $G(V_g)$ obtained a short time after the switch to F_1 is essentially identical to the equilibrium result under F_2 ! In other words, the system retains a memory of the value of the field at which it was allowed to equilibrate. This observation, and the eventual forming of the more prominent and sharper dip [17] appear to be a replica of the $T_2 \rightarrow T_1$ experiment described elsewhere [5]. At the same time, note that, immediately after the $F_2 \rightarrow F_1$ switch one faces an ambiguous situation; Reading the value of G one concludes that the system is already under F_1 . However, judging by the shape of $G(V_g)$ (which is indistinguishable from its steady-state shape under F_2), one may just as well

FIG. 12: Memory of a previous state experiment switching between a relatively high field ($92V/cm$) and an near ohmic field ($0.45V/cm$). The figure shows the anomalous field effect (subtracting the antisymmetric component from the $G(V_g)$ scan), under various conditions. Lower graph: Starting from equilibrium under $92V/cm$ and switching to $0.45V/cm$. Upper graph: Starting from immediately after switching back from $F = 0.45V/cm$ to $92V/cm$. Same sample as in figure 9.

conclude that the system is still under F_2 . These experiments then demonstrate that two ‘thermometers’ attached to the same system (namely, the *value* of $G(T^*)$, and the *shape* of the function $G(V_g, T^*)$) may give quite different readings. This is one of the earmarks of a far-from-equilibrium situation [16].

The current version of this ‘memory-of-a-previous-state’ employing F instead of T has the advantage of the speed and accuracy alluded to above. This also makes

it feasible to carry out the complementary procedure - go from the near-equilibrium ‘cold’ state to the ‘hot’ state that, for technical reasons, was not feasible with the $T_2 \rightarrow T_1$ experiment [18]. Note (upper graph in figure 12) that following the $F_1 \rightarrow F_2$ switch, the sharper appearance of the dip that characterizes its shape at the low field is essentially lost, and the shape of $G(V_g)$ is much closer to the near-equilibrium shape eventually attained than in the respective situation of the complementary case. Note however that the conductance immediately after the switch is still somewhat lower than its asymptotic value, which is consistent with the time-evolution of the conductance in figure 11 (see also reference [19]). This illustrates again that changing F (or T) in either direction is accompanied by a two-stage conductance change; an initial fast change δG_f followed by a sluggish change δG_s that has the same sign as δG_f . Naturally, this effect should be taken into account when analyzing experiments such as that in figure 10. The asymmetry in the resulting effects of ‘cooling’ versus ‘heating’ presumably reflects the difference between relaxation and excitation; relaxation is slow while excitation is fast (see, for example figure 1).

In summary, we have described a number of experimental procedures designed to probe the dynamics of electron glasses as function of temperature and fields. These methods, applied to crystalline indium-oxide films consistently exposed a non-trivial dynamics. Namely, the dynamics associated with relaxation processes became more sluggish with temperature or when measured using non-ohmic fields. It is tentatively conjectured that such a behavior reflects the dynamics expected of a quantum glass where diffusion in phase space is controlled by tunneling in the presence of dissipation [3]. Experiments on other type of materials are planned to further check on this conjecture. At any rate, that dynamics which slows down with temperature is attainable at some range of parameters must be viewed as a constraint on any model for the electron glass.

This research was supported by a grant administered by the US Israel Binational Science Foundation and by the Israeli Foundation for Sciences and Humanities.

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